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Miocene carbonates of the Luconia province, offshore Sarawak: implications for regional geology and reservoir properties from Strontium-isotope stratigraphy

VOLKER C. VAHRENKAMP

Sarawak Shell Bhd., EPG-PRO
Locked Bag #1
98009 Miri
Sarawak

Abstract: The Luconia Province, offshore Sarawak, Malaysia, is one of the largest SE-Asian carbonate provinces with more than 200 platforms and gas reserves exceeding 40 Tscf. The application of the Sr-isotope technique integrated with core, log and seismic data significantly refines the stratigraphy of the province despite extensive diagenetic alteration. Based on the new data, a unified concept of platform evolution is tied to global sea-level variations and the regional distribution of reservoir architecture. Evidence is presented for major karstification during and after platform growth and its influence on the regional distribution of reservoir properties.

Sr-isotope analyses (n_{total} = 137; data range: 0.70849–0.70903 for NBS987 = 0.710230) suggest that the carbonate platforms of the Luconia province are Early to Middle Miocene in age. The Sr-isotope signature is apparently unaffected by diagenetic stabilization from metastable carbonates to low-Mg calcite while dolomitization caused alteration of the isotope ratio. Growth and demise of the province can be correlated with a second-order eustatic sea-level cycle (TB2). Major karst horizons and flooding, aggradation and progradation packages are linked via step-changes in isotope signature to third order eustatic sea-level fluctuations. Simultaneous with the second order sea-level drop (late Middle Miocene) the influx of siliciclastics split the province into a southern part with low relief carbonate banks and a northern part with high relief platforms. All growth terminated at the end of the Middle Miocene. Low relief banks were buried while high relief platforms were karstified prior to drowning (Late Miocene-Pliocene). The regional distribution of pore types, porosity and permeability is linked to the duration of exposure and burial diagenesis. In the karstified platforms of the northern part drilling losses are common.

INTRODUCTION

The late Oligocene to Miocene was a period of widespread carbonate deposition in southeast Asia (Epting, 1980; Fulthorpe and Schlanger, 1989; Ehrlich *et al.*, 1993; Saller *et al.*, 1993; Gucci and Clark, 1993; Sun and Esteban, 1994). Many of these Late Tertiary carbonate sequences have been the target of hydrocarbon exploration with numerous gas and oil reservoirs being discovered [i.e. Malaysia: Central Luconia (Epting, 1980, 1989); Philippines: Nido (Withjack, 1985) and Malampaya (Shell Philippines); Indonesia: Arun (Abdullah and Jordan, 1987; Jordan and Abdullah, 1992), NW Java Sea (Yaman *et al.*, 1991); Ramba (Longman *et al.*, 1987); South Lho Sukon (Maliki and Soenawari, 1991), Natuna (May and Eyles, 1985; Rudolph and Lehman, 1989); China: Liuhua, Pearl River (Moldovanje *et al.*, 1995)].

The Luconia province, offshore Sarawak, Malaysia, is one of the largest of the southeast Asia carbonate provinces (Fig. 1). Over an area of 240 by 240 km more than 200 Miocene carbonate platforms have been mapped, ranging in size from a few to more than 200 square kilometers (Fig. 1). While carbonate deposition is still ongoing at the northern extent of the province in the Luconia shoals, most platforms have been buried by successive prograding marine deltaic siliciclastics (Ho, 1978; Epting, 1980, 1989; Aigner *et al.*, 1989). To date more than 40 of the carbonate platforms have been drilled and more than 20 were found gas bearing with reserves estimated to exceed 40 Tscf.

Despite their economic importance relatively little is known about the chronostratigraphy of the platforms as there are no age diagnostic fossils preserved in the shallow water carbonates. Hence, no age determinations more precise than a general Miocene age are possible. So far, the ages of the top carbonate horizons were constrained only indirectly from dating the overlying clastics. However, because reservoir architecture, karstification, and regional diagenetic trends directly influence reservoir property distribution and hence development and production of these platforms, it is necessary to gain a better understanding of the

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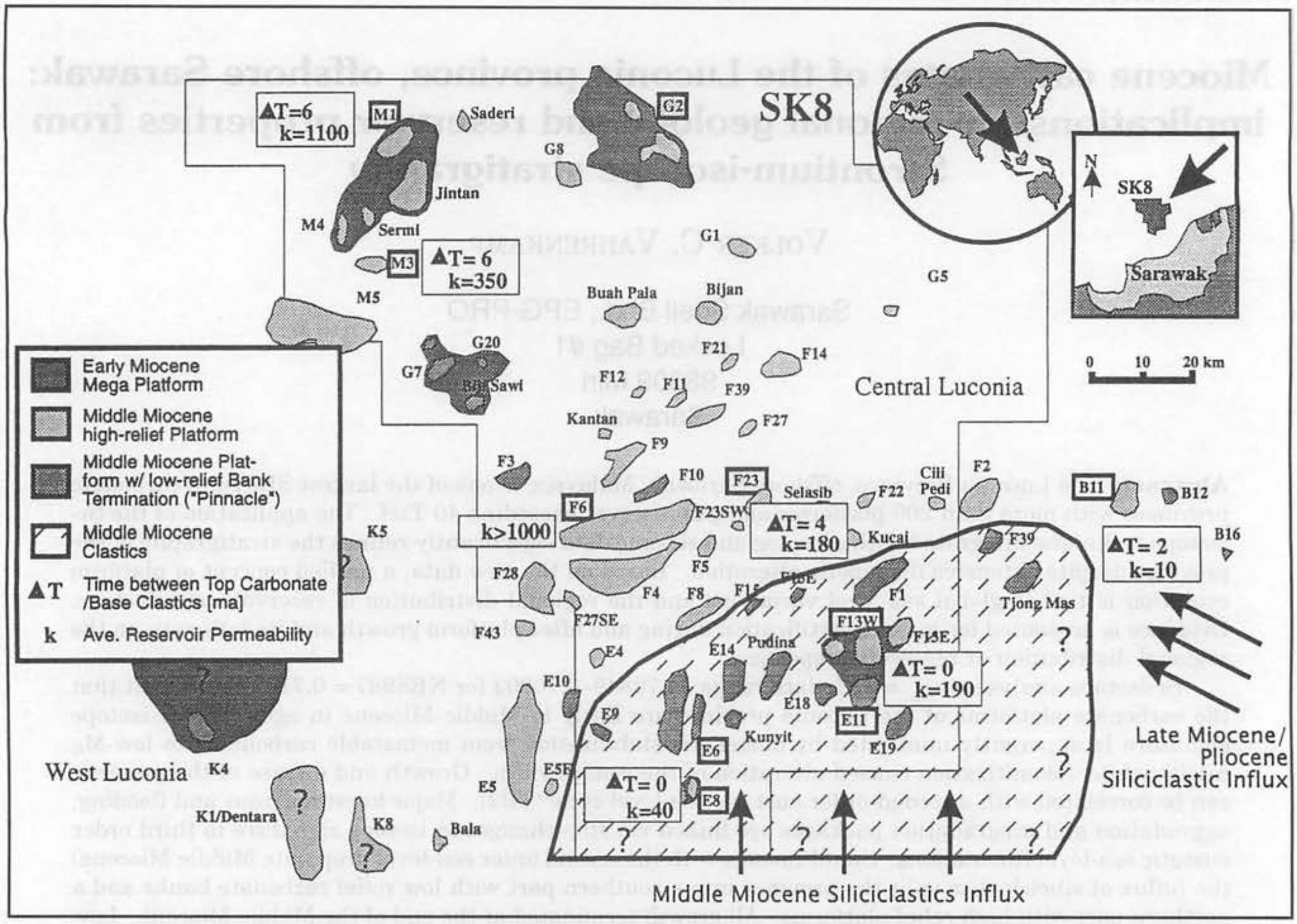

Figure 1. Carbonate platforms of the Central Luconia Province. Platforms with Sr-isotope data are marked by boxes. Note the areal distribution of the age difference between top carbonate and overlying clastics (ΔT) and of the average reservoir permeability (k) [mD] from production tests.

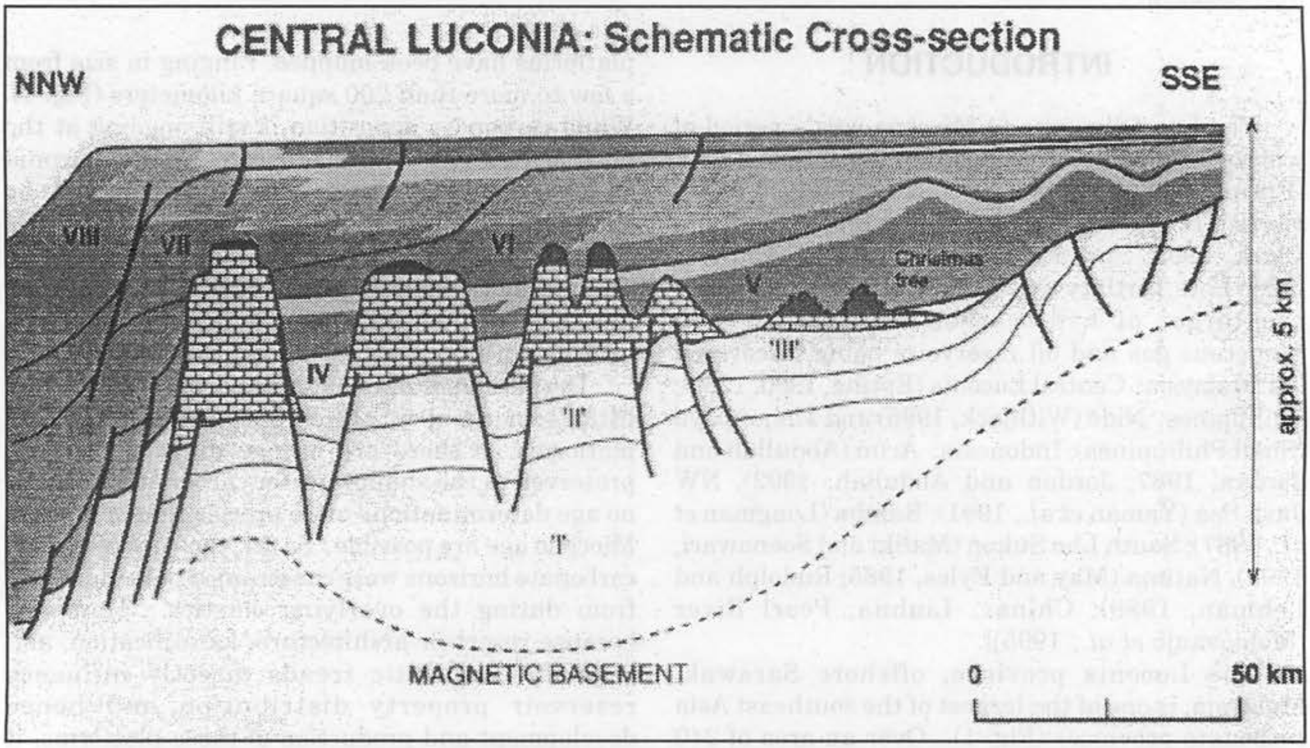

Figure 2. Schematic cross-section through the Central Luconia Province. Carbonate platforms are overlain by Late Miocene to Pliocene prograding clastic sequences. Christmas tree refers to low relief carbonate banks interfingering with clastics (modified from Epting, 1980).

stratigraphy and post-depositional history of Central Luconia carbonates.

It is the aim of this paper to:

- refine the stratigraphy of the Central Luconia carbonate platforms by dating carbonate sequences with Sr-isotope stratigraphy.
- investigate whether growth and demise of the province was driven by eustasy or another external mechanisms such as local tectonics and/or siliciclastic sediment supply.
- document whether a correlation exists between platform growth and demise and regional diagenetic trends which influence the production behavior of Central Luconia gas reservoirs.

PREVIOUS WORK

Carbonate deposition in the Luconia province was believed to have started during the early Middle Miocene on structural highs of faulted Upper Eocene to Lower Miocene holomarine and neritic siliciclastics (Fig. 2; Ho, 1978). A cyclic growth pattern with several transgressive and regressive sequences has been recognized and correlated in several platforms to the large scale sedimentary cyclicity of Sarawak (Ho, 1978; Epting, 1980, 1989; Aigner *et al.*, 1989). During the Middle Miocene to Pliocene fluvio-deltaic clastics prograded in several cycles from Borneo north-northwestward into the South China Sea burying Luconia platforms (Fig. 2). Drowning of the carbonates has been associated with decreasing water quality and increasing subsidence in front of the advancing siliciclastic wedges with pronounced back-stepping of the platforms during final growth phases (build-in phase of Epting, 1980). Thus, top carbonate ages were believed to decrease from the late Middle Miocene to the Pliocene on a southeastern to northwestern transect in the buried part of the province with deposition continuing to date beyond the furthest extent of the clastics in the northernmost part of the province, the Luconia shoals (Fig. 1; Epting, 1980).

STRONTIUM ISOTOPE STRATIGRAPHY

Changes in the marine $^{87}Sr/^{86}Sr$ composition through time have been caused by varying fluxes to the ocean of strontium from the alteration of oceanic and continental rocks (Fig. 3) (e.g. McArthur, 1994 and references therein). Since the Late Eocene, overall Sr-isotope ratios of seawater have become more radiogenic resulting in increasing $^{87}Sr/^{86}Sr$ ratios with time (Burke *et al.*, 1982; Hess *et al.*, 1986; DePaolo, 1986; Hodell, 1991; McKenzie *et al.*, 1988; Beets, 1992; Swart *et al.*, 1995). The overall continuous increase in Sr-isotope ratios of seawater over this time period has been used as a tool to constrain the stratigraphic age of Tertiary shallow marine limestones and dolomites (Saller, 1984; Swart *et al.*, 1987; Ludwig *et al.*, 1988; Vahrenkamp *et al.*, 1988; Vahrenkamp *et al.*, 1991; Beets, 1992; Swart *et al.*, 1995). It is possible to compare Sr-isotope ratios from marine carbonates with the Sr-isotope curve of seawater through time, because carbonates incorporate seawater strontium during their growth as trace element without isotopic fractionation. Ideally, Sr-isotope stratigraphy is therefore conducted on pristine marine precipitates that are believed to have survived completely unchanged from their original composition (Popp *et al.*, 1986; Carpenter *et al.*, 1991). However, due to the metastable character of marine carbonates, diagenesis has usually altered the original mineralogy from aragonite and high-Mg calcite to low-Mg calcite and dolomite. In the Central Luconia province diagenesis has progressed to the point that no original marine carbonates are preserved. Instead, Luconia limestones have been altered to low-Mg calcite and dolomites during extensive diagenesis.

Strontium Isotopes Ratio of Low-Mg Calcite

The Sr-isotope composition of a carbonate mineral is derived from the water involved in its precipitation. Meteoric waters are believed to be the primary medium of low-Mg calcite precipitation (i.e. Bathurst, 1971) and have a negligible Sr content upon entering the rock system. The Sr-isotope signature of the meteoric water is subsequently derived from its interaction with minerals beginning from the moment it enters the rock system until it reaches the site of calcite precipitation. Thus, meteoric waters commonly have Sr-isotope signatures closely associated with that of the terrain they flow through and significantly different from that of seawater. Modern river waters draining continents have an average isotopic ratio of 0.712 compared to 0.709 for modern seawater (McArthur, 1994 and references therein). However, on isolated oceanic islands with essentially no other sources for Sr but limestones (assumed: no volcanic activity and no clastic rocks), the Sr-isotope signature of meteoric waters is acquired from carbonates of marine origin and does not differ much from ratios typical for seawater. In such a setting it has been shown that low-Mg calcites can retain a Sr-isotope signature similar to that of their precursor (Ludwig *et al.*, 1988; Saller and Koepnick, 1990). However, all samples must be evaluated in their context because it is always possible that Sr from external sources or from older or younger carbonates becomes incorporated and that the measured Sr-isotope ratio differs from that of the precursor mineral (Vahrenkamp, 1988).

Strontium Isotopes Ratios of Dolomites

Large scale dolomitization requires the addition of Mg^{2+} from seawater to the rock system. Mass balance calculations have shown that the amount of seawater necessary for dolomitization causes at least a partial resetting of the Sr-isotope signature from the precursor value to that of the seawater involved in dolomitization (Vahrenkamp *et al.*, 1988). Since the $^{87}Sr/^{86}Sr$ ratio of seawater has more or less systematically increased since the early Tertiary, dolomitization will introduce younger apparent ages to the rock, if it occurs significantly later than deposition. Thus, Sr-isotope ratios derived from dolomites indicate the youngest possible age of the rock (it may be older if the precursor memory has been partially or completely deleted) and the oldest possible age of dolomitization (it may be younger if a precursor memory has been retained).

DATA

Sr-isotope analyses were performed on a total of 137 powdered bulk rock samples from 17 cored wells of 11 Luconia platforms (Fig. 1). Core coverage is excellent in Central Luconia with core lengths in several platforms in excess of 1,000 feet with more than 95% recovery. This ensures that the overall sedimentological context of the samples is well constrained. Sample mineralogy was determined by at least one of the following methods: X-ray

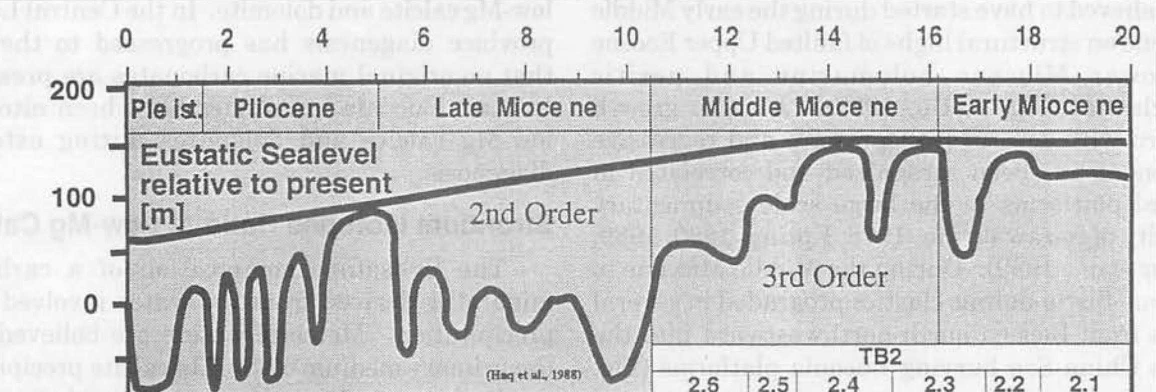

Figure 3. The evolution of Sr-isotopes in seawater over the past 20 million years (from Swart *et al.*, 1995). The shaded fields show the number of samples from Luconia wells that fall into the respective intervals. The stippled lines show the data ranges measured. The Sr curve is correlated with the eustatic sea-level fluctuations reported by Haq *et al.*, 1988. A correlation exists between the curves with sea-level lowstands coinciding with decreases in Sr-isotope ratios.

analysis, grain density measurements or stained thin sections. Most samples are either predominantly low-Mg calcite or dolomite. Only a few samples are mixtures of calcite or dolomite with the minor component exceeding 20% of the total (Table 1). The isotopic compositions were measured on a VG 354 thermal ionization mass spectrometer fitted with 7 collectors. The measured NBS987 $^{87}Sr/^{86}Sr$ value is 0.710221 +/– 0.00002 (95% confidence limit). For comparison with other published data all values were normalized to an NBS987 value for $^{87}Sr/^{86}Sr = 0.710230$. The age of the samples has been established by comparing their $^{87}Sr/^{86}Sr$ signature with a curve of Sr-isotope ratios in seawater through time by Swart *et al.*, 1995 (Fig. 3). Strontium isotope data are supplemented by information from seismic lines, thin sections and logs.

TRANSLATING SR-ISOTOPE RATIOS INTO AGE

Several curves have been published for the Neogene evolution of Sr-isotope ratios in seawater (i.e. Burke *et al.*, 1982; Hess *et al.*, 1986; DePaolo, 1986; Hodell, 1991; McKenzie *et al.*, 1988; Beets, 1992; Swart *et al.*, 1995). For this study the curve by Swart *et al.* (1995) was used (Fig. 3). The curve was synthesized from data published by several authors and has a +/– 1 sigma error envelope. The error introduced by the shaped of the curve results in an age uncertainty of between 0.4 and 3.7 million years for the period of interest. This error is significantly larger than the error determined for the machine and repeat analyses combined (vertical bar — Fig. 3).

RESULTS

Rounded to five significant figures and including an error of +/– 0.00002, data vary between 0.70849 to 0.70903. This corresponds to Early Miocene to Early Pliocene Sr-isotope ratios of seawater (Fig. 3). Of the 137 samples 3 have an Early Miocene Sr-isotope signature, 105 have isotope ratios corresponding to Middle Miocene seawater ratios, 23 sample ratios straddle the Middle Miocene/Late Miocene boundary, one has a Sr-isotope ratio corresponding to a Late Miocene seawater signature and 5 samples have ratios that indicate an age close to the Miocene/Pliocene boundary (Fig. 3).

Overall, Sr-isotope ratios of samples from any particular well are either constant or decrease with depth indicating constant or increasing age with depth within the resolution of the Sr-isotope curve (Fig. 4). Notable exceptions are found in platforms F23, M1, G2 and G10 where samples with signatures indicating younger ages are sandwiched between others associated with older age estimates (Fig. 4).

DISCUSSION

Depositional Age versus Diagenetic Age

Ideally, Sr-isotope ages should increase with depth if the precursor isotope composition remained preserved and/or diagenesis occurred soon after deposition. However, the Sr-isotope age of a section or part of a section can also remain constant if deposition occurred over a time period too short to be further resolved by the Sr-isotope curve. Increasing or constant age versus depth are found in most measured sections (Fig. 4). Most of the dolomite samples have Sr-isotope signatures similar to, or only slightly younger than, those of nearby low-Mg calcite samples (i.e. E11-2 6684). This indicates that some dolomitization occurred soon after deposition since dolomites most likely record the age of diagenesis and not that of the precursor (Vahrenkamp, 1988). Thus, for most studied sections, it can be assumed that the Sr-isotope ages describe a minimum age close to the actual age of the sediments.

However, departures from this pattern are found in platforms M1, F23, G2 and G10. In M1, F23 (Fig. 4) and G10 sections with late Late Miocene and Pliocene Sr-isotope ages are sandwiched between intervals with Middle Miocene dates. In G2 samples with Middle Miocene ages are found below a section characterized by Early Miocene Sr-isotope ages. Most of these anomalous data are associated with dolomites and thus document a stage (or several stages) of diagenesis occurring several million years after deposition during the Middle Miocene (G2) and near the Miocene/Pliocene boundary (M1, F23 and G10). I speculate that burial marine diagenesis was triggered either during reflooding of the platforms after a prolonged period of exposure (see discussion below) or as a result of Late Miocene sea-level lowstands associated with the Messinian crisis (Hsü *et al.*, 1977).

Pre-Platform Carbonates

Strontium-isotope ratios assign an Early Miocene age (16.9–19.5 Ma) to a carbonate lens in a clastics interval from below the Luconia platform section (Fig. 5 — TB2.1 or TB2.2; Fig. 4). This indicates that at least in G2 Luconia platform carbonates are Early Miocene or younger (TB2.2 or younger).

Growth and Cyclicity of Central Luconia Platforms

The oldest measured Sr-isotope dates of Luconia platform carbonates are from F13, E8 and G10 indicating an early Middle Miocene age. This suggests that Luconia platforms probably originated in the late Early Miocene since none of the data cover the base of the platform section. The majority of the drilled sections, however, are Middle Miocene in age (Figs. 4, 5). Only the uppermost sections in four of the investigated build-ups reach the end of the Middle Miocene or may even extend into the early Late Miocene. This finding supports previous interpretations on the upstart of Luconia platforms but is in marked contrast to the previous assumption

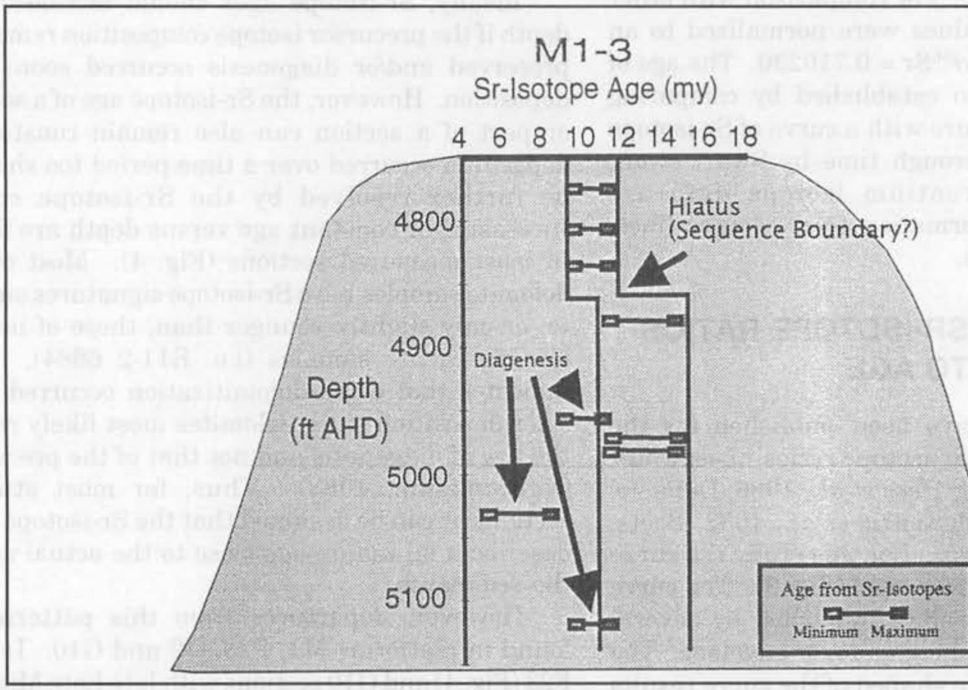

Figure 4a. Sr-isotope ages of well M1-3. Data indicate a Middle Miocene age (TB2.4 and younger). Note the shift in isotope ages (top TB2.4 or 2.5) and the effect of diagenesis.

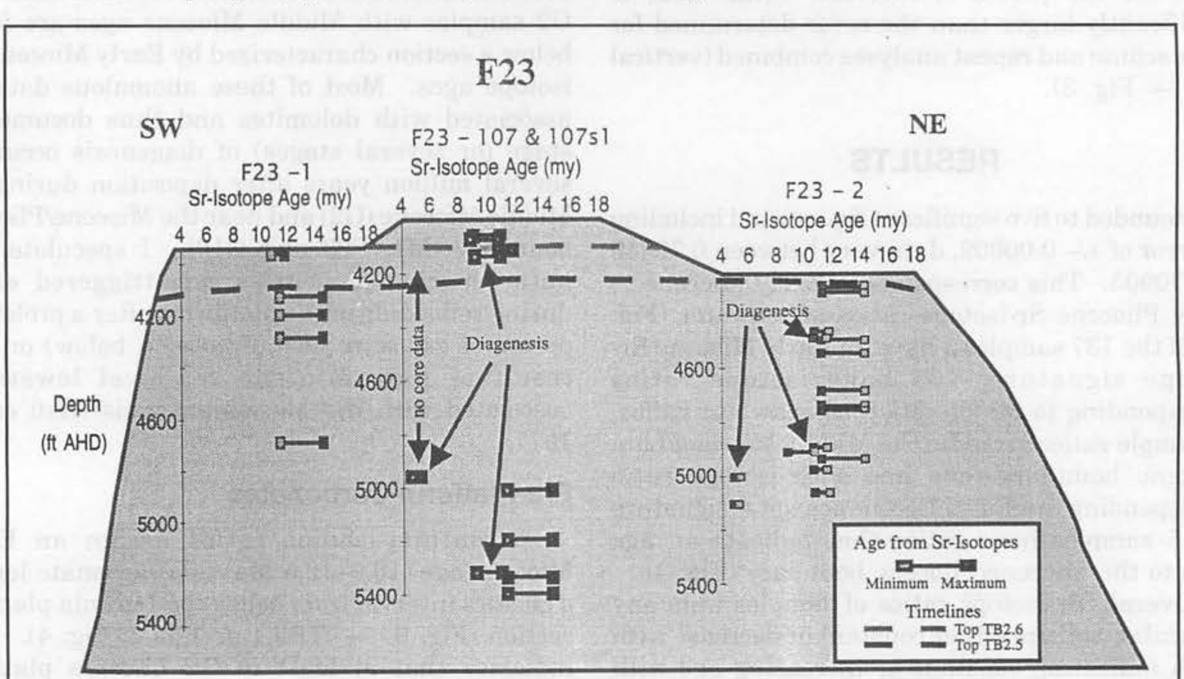

Figure 4b. Sr-isotope ages of three wells from F23. The wells are aligned along a SW-NE cross-section. Data indicates a Middle Miocene age (TB2.4 and younger).

that deposition in the buried central and northern parts of the province continued through the Late Miocene into the early Pliocene (Ho, 1978; Epting, 1980, 1989; Aigner *et al.*, 1989).

Carbonate platform growth commonly closely mirrors sea-level fluctuations because it is essentially confined to within 50 m depth of the sea surface ("dip stick" of Schlager, 1992, p. 78). Considering the several thousand feet thick carbonate sections and the lack of major faulting and tectonic activity it is likely that Luconia platform growth was govern by eustatic sea-level fluctuations and not by autocyclicity (sensu Ginsburg, 1971) or some changing tectonic regimes. The periods of platform origination (late Early Miocene), most prolific platform growth (late Early to early Middle Miocene) and platform disintegration (late Middle Miocene) correspond in time to a second order eustatic sea-level cycle (TB2) with six third order cycles on the global sea-level curve (Haq *et al.*, 1988; Fig. 3). Core analysis provides evidence for the influence of eustatic sea-level fluctuations on Luconia platform growth. The fundamental building blocks of the investigated carbonate sections are meter scale cycles (Sulaiman, 1995) which are stacked into several larger scale cycles corresponding in part to those defined by Epting (1980). Even though some of the major cycle boundaries are associated with shifts in the age signature derived from Sr-isotope (i.e. in M1-3, F23 and E8-4; Fig. 4), the absolute changes in the Sr-isotope ratios are generally not large enough to confidently identify major hiatuses during platform growth and/or individual third order cycles. Thus, even though cyclicity and exposure horizons are clearly recognized in cores, on the resolution of the Sr-isotope curve deposition was (more or less) continuous throughout the Middle Miocene and no major hiatus exists within the drilled section.

Despite the only minor changes in the absolute isotope ratios, corresponding ages are grouped into several albeit overlapping time intervals. While this may reflect growth during several consecutive third order sequences it may also just be an artifact derived from the sinusoidal shape of the Sr-isotope age curve. However, since there appears to be a correlation between third order eustatic sea-level fluctuations and short term changes in the Sr-isotope ratios (Fig. 3) there might be merit in assigning sections with consistent age estimates to specific third order sequences. This would provide a much refined tool for correlation between individual platforms.

Demise of the Central Luconia Province

The demise of the Luconia province is characterized by several distinct back-stepping events. The first major back-stepping caused the segmentation of larger platforms (e.g. Jintan/M complex; E11/F13 complex, E8; Figs. 1, 5). While this event has not been dated directly, it apparently occurred in the Early Miocene prior to the first dated sequence in the earliest Middle Miocene and was associated with a major karstification event

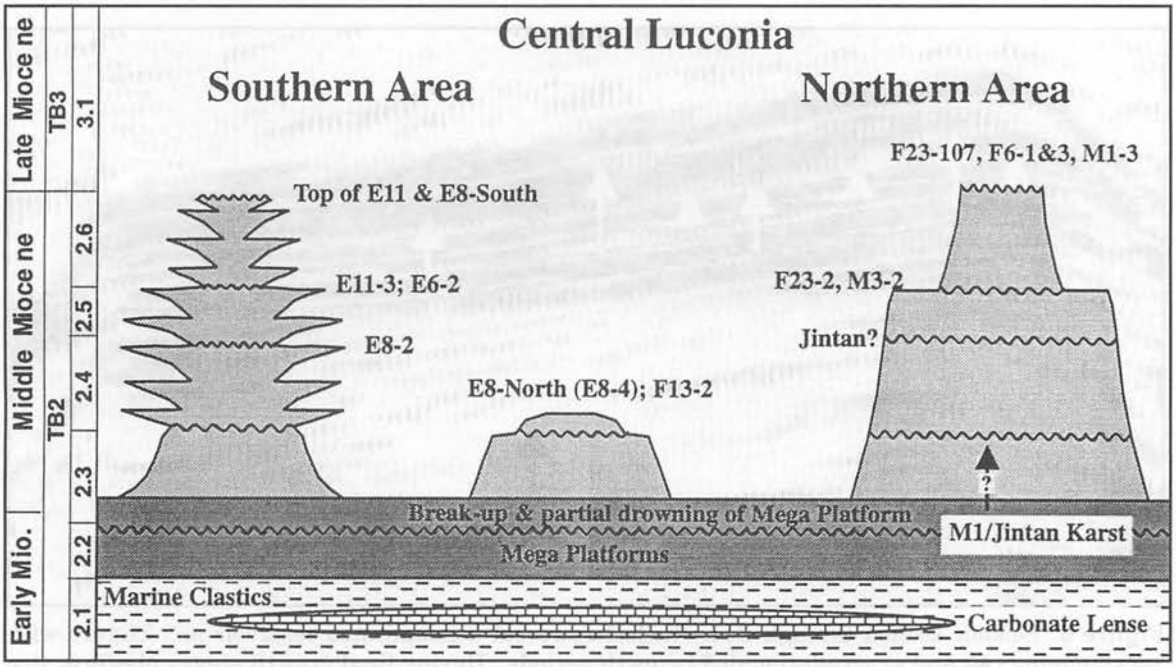

Figure 5. Summary of Central Luconia stratigraphy with the top carbonate ages from several wells and platforms. The start-up of the mega platform is tentative. An alternative start-up is the beginning of TB2.3. This would move the age of the M1/Jintan Karst to the top of TB2.3.

(Fig. 5). It is tentatively correlated with the sea-level drop following cycle TB2.2 of the Haq *et al.* (1988) sea-level curve. During reflooding in the earliest Middle Miocene (TB2.3) a number of smaller platforms re-established (E11, F13, M1, M4, E8 North & South) while major parts of the previous mega platforms drowned. Evidence exists from F13 that at least in the southern regions close to Borneo the fragmentation coincided with a clastic influx (Sulaiman, 1995).

The second major step in the demise of the province occurred after a period of renewed significant aggradation of the remnant platforms during the early Middle Miocene (TB2.3; Fig. 5). Shallow water carbonate deposition was terminated by a regional exposure. Karstification at this horizon has been documented in several platforms and is probably responsible for severe mud losses during drilling of some wells in platforms M3 and M1. At the same time and probably related to the sea-level lowering, encroachment of siliciclastics from Borneo northwards onto the Luconia Province caused a subdivision of the Luconia Province into a southern area with low relief carbonate banks and a central and northern area with steep flanked platforms (Fig. 1).

In the southern area, upon re-flooding (sea-level rise of TB2.4), some of the platforms that came under the influence of siliciclastics, could not re-establish and drowned (F13, E8-North; Fig. 5). Enigmatically, other platforms close-by survived and continued to grow sections in excess of a 300 meter thickness for the remainder of the Middle Miocene, albeit as low relief carbonate banks interfingering with clastics (e.g. E11, E8 — Fig. 5). Deteriorating growth conditions and/or prograding clastics caused areal decrease of the platforms and finally burial by coeval clastics latest at the end of the Middle Miocene (Epting, 1980, 1989; Aigner *et al.*, 1989; Fig. 5). A further differentiation of the section based on Sr-isotopes is difficult because the uppermost sections of these platforms have no data coverage (i.e. E8 and E11). However, the topmost measured sections do already reach the second youngest Middle Miocene age bracket documented from steep flanked platforms of the central and northern area (i.e. F23, F6, M1). Contrary to previous interpretation (Epting, 1980) I now assume that the final cessation of carbonate growth is coeval throughout the Central Luconia province (sea-level drop after TB2.6).

In the central and northern part of the province evidence for further back-stepping of the steep-flanked platforms during the latter part of the Middle Miocene comes from seismic and core/log data. Deposition during this period is distinctly cyclical on several orders with numerous exposure and flooding events. Initially, the remnant platforms maintained their size after each major flooding event by aggrading and prograding back out to be previously established margin (Fig. 6). Finally, however, growth conditions became too bad or time too short to re-establish previous margins, causing a marked decrease in the areal extent of

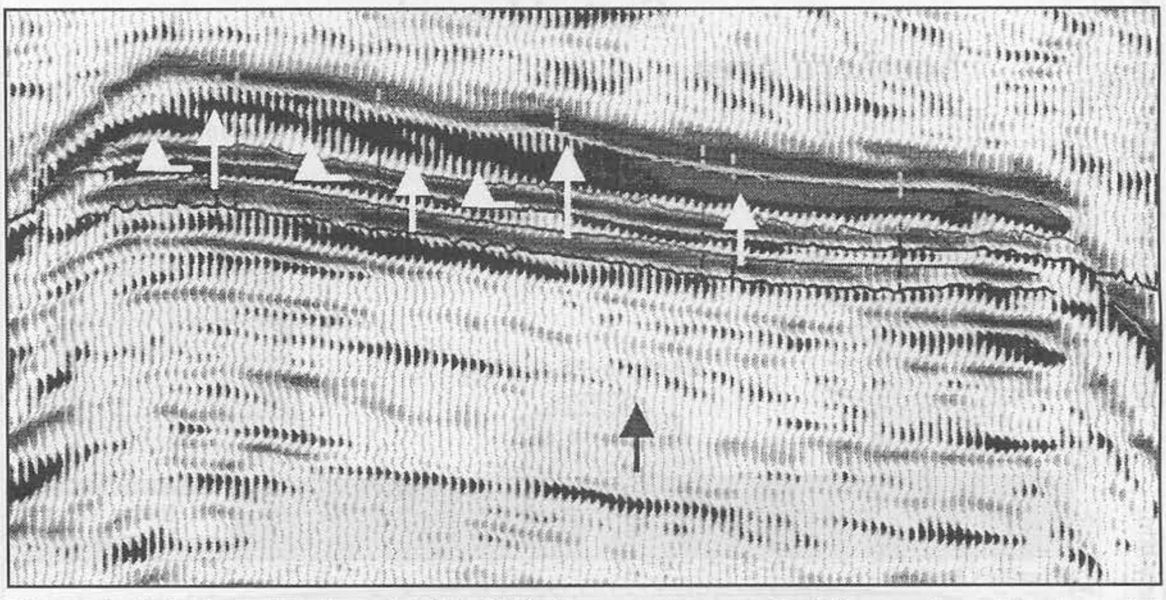

Figure 6. Seismic section through B11. Reflectors reveal a complicated reservoir architecture with backstepping (▲) and progradational(↑) growth periods. During final growth stages platform size decreased: shallow water carbonate deposition remained upwind — open marine carbonates dominated downwind. Seismic attribute variations indicates potential for lower reservoir porosity in the open marine carbonates of the downwind side (↑).

platforms. Shallow water carbonate deposition continued in up-wind positions. Down-wind areas, which during the later stages of previous progradational periods were sites of lagoonal or reefal deposition, only received deeper marine grainstones interlayered with argillaceous limestones (Fig. 6). Platform geometries and internal architectures are closely linked to paleo-wind directions. Windward margins are steep, remained more or less stationary through time and were probably reef lined. Leeward margins have bulging outlines and are more gently sloping (Fig. 7) with an internal architecture that shows downwind progradation during sea-level highstands and upwind back-stepping during periods of flooding (Fig. 6). At the end of the Middle Miocene platforms had significantly decreased in size (i.e. F6, F23) and finally growth was terminated probably as a result of a significant third order sea-level drop at the end of the TB2 second order cycle. Contrary to the previous drowning model proposed by Epting (1980) this interpretation assumes that platform growth was terminated by sea-level lowering and subareal exposure.

Karstification during the early Late Miocene

The interpretation that final termination of platform growth in the central and northern part of the Luconia province was caused by subareal exposure at the end of the Middle Miocene, rather than by drowning in front of an advancing clastic wedge, is corroborated by other evidence. Depending on the position of the platform, the difference in age between the carbonates and the overlying pro-deltaic clastics increases from coeval in the southern parts of the province to more than 6 million years in its northern extent (Figs. 1, 2). Pelagic carbonates between shallow water carbonates and overlying clastics have not been documented. Such a long hiatus either implies exposure or significant submarine erosion.

Meteoric diagenesis has played a major role in porosity and permeability development of Central Luconia carbonates with porosities reaching and exceeding 40% and permeabilities in the Darcy range (F6, M1). The top carbonate sections in some cores are severely karstified, exhibiting discoloration, large leaching-enhanced vuggy pores and other features typical of exposure (F23-107, F6-1). Epting (1980) concluded that buildups were apparently emergent over a considerable period at the end of their growth prior to being covered by clastics. In the center of platform M1 (Fig. 1) marine shales which fill vuggy porosities down to 250 feet below top carbonate have been dated as latest Late Miocene to earliest Pliocene (NN12A). This suggests development of a well connected karst system prior to burial of the platform by marine shales which is corroborated by severe drilling losses in some wells.

The decrease in age of the clastic cover along the south-north profile suggests that exposure lasted significantly longer in the northern parts of the province. Longer exposure may impact production behavior of platforms assuming that more leaching results in higher porosities and permeabilities. This is supported by regional trends of average porosities and well test permeabilities (Fig. 1).

Drowning and Burial

Previously, the final period of platform growth was classified as a transgressive cap sequence (Epting, 1980, 1989), implying that the platforms drowned during a flooding event. However, evidence for the transgressive cap comes from localities where deposition was already influenced by significant siliciclastic input (southern realm low relief banks) or from leeward positions on high relief platforms which received relatively deep water, open marine carbonates as a result of back-stepping (e.g. F23-2; F6-2, F6-6; M1-3). However, windward and central parts of the high relief platforms had continuous shallow water deposition until the termination of carbonate deposition followed by subareal exposure (e.g. F23-1 & 107; F6-1, M3-2). The duration of exposure and karstification is unclear. However, drowning occurred sometime during the Late Miocene in front of a clastic system which, based on seismic evidence, advanced northwestward from the Baram delta. This siliciclastic source is different from that which prograded northward from the Bintulu/Miri area during the late Middle Miocene causing termination of carbonate growth in the southern part of the Luconia province.

Seismic evidence suggests that platforms had already drowned and subsided to significant water depth prior to the arrival of the Baram clastics (Fig. 2). Several factors may have combined to cause drowning:

- Late Miocene uplift of the Crocker Range in the Sabah hinterland provided a prolific source for clastics (Hutchison, 1995).
- Progradation of the Baram delta may have been aided by the eustatic sea-level lowstands of the early Late Miocene (Haq *et al.*, 1988).
- The rapid infill of the deep basin eastward of the West Baram Line may have added a substantial crustal load causing additional tectonic subsidence of the Luconia province.

The new source of siliciclastics, the subsidence pulse from loading, the rapidly rising eustatic sea-level at the end of the Late Miocene, and the additional decrease in carbonate growth potential due to siliciclastic and organic input into the

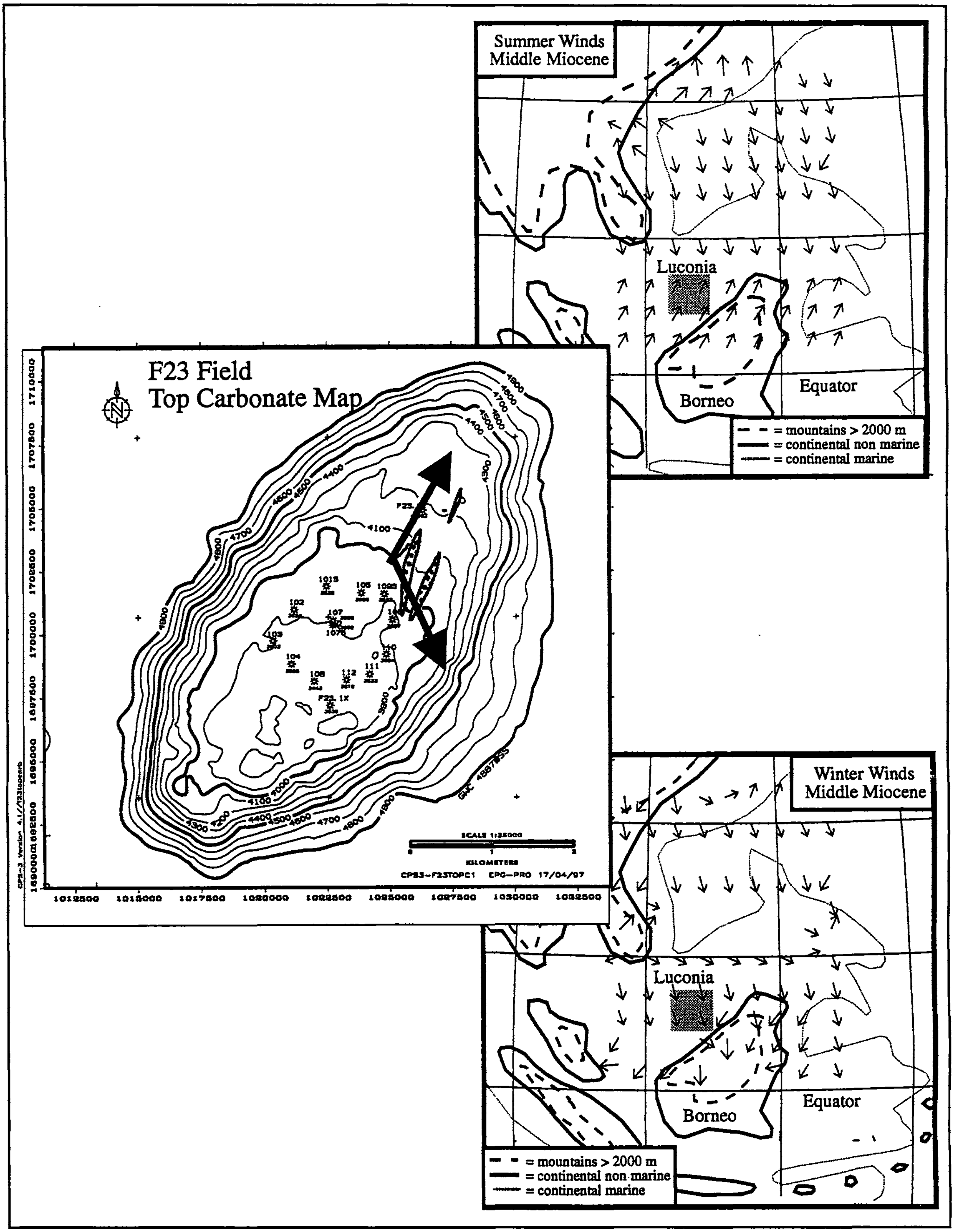

Figure 7. Top carbonate map of F23 platform. The platform is asymmetric with steep SSW to NW flanks and more gently dipping SSE to NE sides. Bulging margins coincide with the down-wind directions indicated on paleo-winds maps of the area during the Miocene. This signals preferred sediment transport to the NNE and the SE during the Middle Miocene in the Luconia area.

seawater from hinterland erosion may have combined to cause drowning and burial of the resubmerging Luconia platforms during the end of the Late Miocene.

CONCLUSIONS

1. Sr-isotope dating is an excellent tool to constrain the stratigraphy of the Luconia carbonate sequence despite their extensive diagenetic alteration.
2. Sr-isotope analyses suggest that the carbonate platforms of the Luconia province are Early to Middle Miocene in age. Deposition ceased at the end of the Middle Miocene probably due to a long period of platform exposure. The most widespread carbonate deposition occurred during the Early Miocene. Following exposure and karstification at the end of the Early Miocene, platforms backstepped in several episodes leading to a stepwise drowning of the original mega platforms. Growth and demise of the Luconia province are distinctly cyclic on several orders. Overall they accumulated during a second-order eustatic sea-level highstand and drop. Major karst horizons and the thicker flooding, aggradation and progradation packages are linked to third order eustatic sea-level fluctuations. Meter scale cycles form the fundamental building blocks of the sections.
3. Simultaneous with the second order sea-level drop, siliciclastics started to transgress into the Luconia province. Clastics advanced first northwards from the Bintulu/Miri area during the latter half of the Middle Miocene, splitting the province into a southern area with low relief carbonate banks and a central and northern area with high relief platforms. The low relief banks of the southern part of the province were buried during the end of the Middle Miocene by clastics from this source. The second clastic incursion advanced northwestward from the Baram delta. It reached the province after the cessation of carbonate growth during the Late Miocene and the Pliocene burying the central and northern platforms and providing the seal for the carbonate reservoirs of this area.
4. In the central and northern area platforms experienced prolonged exposure and karstification from the end of the Middle Miocene prior to drowning in front of the advancing Baram delta siliciclastics. The duration of exposure depends on the distance from the delta and varies from a maximum of approximately 2 million years in B11/B12 to 6 million years in M1/M3.
5. The regional distribution of pore types, porosity and permeability are linked to the growth history, and the time available for exposure and burial diagenesis. Dolomitization and intercrystalline porosity are prevalent in the southern part of the province. Platforms in the central and northern parts are predominantly calcitic with moldic and chalky porosities. Overall porosity and permeability increase northwards as a function of more time available for meteoric diagenesis and karstification prior to burial and less time available for burial diagenesis prior to hydrocarbon charge.
6. Subareal exposure and karstification played a prime role in reservoir development both during cyclic growth of the platforms and during the hiatus prior to burial. In these heavily karstified platforms drilling losses can be expected throughout the section but are probably most frequent in cave systems at third order cycle boundaries associated with subareal exposure and sudden facies shifts.

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